Formation of neutron-rich and superheavy elements in astrophysical objects

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We calculate the reaction and the fusion cross-sections of neutron-rich heavy nuclei taking light exotic isotopes as projectiles. Results of neutron-rich Pb and U isotopes are demonstrated as the representative targets and He, B as the projectiles. The Gluaber Model and the Coupled Channel Formalism are used to evaluate the reaction and the fusion cross-sections for the cases considered. Based on the analysis of these cross-sections, we predict the formation of heavy, superheavy and super-superheavy elements through rapid neutron/light nuclei capture r-process of the nucleosynthesis in astrophysical objects.

Formation of superheavy elements (SHE) in the laboratory is one of the most challenging problem in Nuclear Physics. So far the synthesis of Z=118 element has been possible [1]. Efforts are on to synthesise still heavier elements in various laboratories all over the world. It is certain that if an element is created through human efforts then definitely it must be present naturally somewhere in the Universe. Thus the mode of formation of superheavy or super-superheavy element in astrophysical object is a fundamental question in the field of Nuclear Astrophysics. In this context, it is mandatory that the superheavy element with Z=118 and higher atomic numbers are present in the object like relativistic jets of $\gamma - rays$ bursts (GRBs) or supernovae jets near the nascent neutron star. It has been reported in Ref.[2], and the stability of the most stable superheavy elements could be as high as 10^9 years in some of the calculations [3].

Study of unstable nuclei with radioactive ion beam (RIB) facilities has opened an exciting channel to look upto some of the crucial issues in the context of both nuclear structure and astrophysics [4]. Unstable nuclei play an influential, and in some cases dominant role, in phenomena of the cosmos such as Gamma Ray Bursts.

The direct study of stellar properties in ground-based laboratories has become feasible, due to the availability of RIBs; for example the study of ^{18}Ne induced neutron pick-up reaction could reveal information about the exotic ^{15}O+^{19}Ne reaction occuring in the CNO cycle in stars. Study of the structure and the reactions of not only unstable light exotic but also of the superheavy and the super-superheavy nuclei is therefore required to improve our understanding of the astrophysical origin of atomic nuclei and the evolution of stars and their death.

In a recent study, Satpathy et al. [5] claimed the neutron-rich U and Th-isotopes are thermally fissile and could release orders of magnitude more energy than ^{235}U in a new mode of fission decay called *multi-fragmentation fission*, which happend frequently in astrophysical objects. The main objective of the present letter is to study the reaction (σ_r) and fusion (σ_f) cross-sections of neutron-rich U and some other interesting exotic isotopes, which are related to the formation of neutron-rich, SHE and super-SHE elements in the Universe.

The value of σ_r is calculated by using the most recently developed effective field theory motivated relativistic mean field (E-RMF) nuclear densities [6], in conjunction with the Glauber model. However, σ_f is estimated in the non-relativistic coupled channel calculation. From the calculated reaction and fusion cross-sections, we

look for the formation path of neutron-rich, SHE and super-SHE nuclei in the cosmos. The theoretical formalism to calculate the nuclear reaction cross-section using Glauber approach has been given by R. J. Glauber [7]. The standard Glauber form for the reaction cross-section at high energies, is expressed [7] as:

$$\sigma_r = 2\pi \int_0^\infty b[1-T(b)]db \;, \qquad (1)$$

where $T(b)$, the transparency function, is the probability that at an impact parameter b the projectile passes through the target without interaction. This function $T(b)$ is calculated in the overlap region between the projectile and target where the interactions are assumed to result from single nucleon-nucleon collision and is given by

$$T(b) = \exp\left[-\sum_{i,j} \overline{\sigma}_{ij} \int d\vec{s}\,\overline{\rho}_{ti}\,(s)\,\overline{\rho}_{pj}\left(\left|\vec{b}-\vec{s}\right| s\right)\right] . \qquad (2)$$

Here, the summation indices i, j run over proton and neutron numbers and subscript p and t refers to projectile and target respectively.

The original Glauber model is designed for high energy projectile, like relativistic proton reactions. It fails to describe the collisions induced at relatively low energies. In this case, the straight-line trajectory is modified because of the presence of the Coulomb field of the target and projectile. In such cases the present version of Glauber model is modified in order to take care of finite range effects[8] in the profile function and the Coulomb modified trajectories. Thus for finite range approximations, the transparency function is given by

$$\begin{aligned} T(b) \;\; = \;\; \exp\Bigg[&-\int_P \int_T \sum_{i,j} \left[\Gamma_{ij}\left(\vec{b}-\vec{s}+\vec{t}\right)\right] \\ &\overline{\rho}_{Pi}\left(\vec{t}\right)\overline{\rho}_{Tj}\left(\vec{s}\right) d\vec{s}d\vec{t}\Bigg] \;. \qquad (3) \end{aligned}$$

Here the profile function Γ_{ij} is given by

$$\Gamma_{ij}(b_{eff}) = \frac{1-i\alpha}{2\pi\beta_{NN}^2}\sigma_{ij}\exp\left(-\frac{b_{eff}^2}{2\beta_{NN}^2}\right) \;, \qquad (4)$$

where $b_{eff} = \left|\vec{b}-\vec{s}+\vec{t}\right|$, $\vec{b}$ is the impact parameter and $\vec{s}$ and $\vec{t}$ are just the dummy variables for integration over the z-integrated target and projectile densities. The values of the parameters, $\bar{\sigma}_{ij}$, α and β_{NN} are taken from Ref. [9]. The detailed formalism is available in Ref.[10].

The E-RMF density with G2 parameter set [6,11] is used as input for the evaluation of σ_r. For the details of the calculation of ground state properties of finite nuclei and the procedure of estimation of nuclear cross-section, we refer the reader to Refs. [10,11,12].

To compute the fusion cross-section σ_f we follow the coupled-channel calculations including all orders of coupling. This is done in a non-relativistic framework. The computer code CCFULL as developed in Ref. [13] is used. The fusion cross-section is given by the formula [13]:

$$\sigma_f(E) = \sum_J \sigma_J(E) = \frac{\pi}{k_0^2}\sum_J (2J+1)P_J(E), \qquad (5)$$

with $P_J(E)$ is the inclusive penetrability and the other symbols have the standard meaning as defined in [13].

It was shown in our earlier papers that the densities taken from relativistic mean field formalism, and used in the frame-work of Glauber model [7,12] to evaluate the differential and total reaction cross-section is quite successful for light systems [10]. Now we extend the model to calculate the total reaction cross-section considering light exotic nuclei as projectile and heavy neutron-rich isotopes as target. Here, we calculate as the representative cases for the reaction cross-section of neutron-rich Pb and U isotopes taking exotic He and B nuclei as incident projectile.

In Fig. 1 the reaction cross-section σ_r for ^{4}He+^{208,228,248,278}Pb, ^{10,15,17,20}B+^{208}Pb, ^{4}He+^{235,250,270,290}U and ^{10,15,17,20}B+^{235}U are presented. From the calculated results, the increase in σ_r is quite substantial with the target mass. The same observation is also applicable, while increasing the mass of the projectile (keeping the target mass constant). In any of these cases, the reaction cross-section becomes favourable with either increase of projectile mass or the mass of the target or both. The enhance-

ment can be understood by the simple classical expression of the cross-section πR^2 (R=radius of the nucleus) where the increase is due to the larger size of the nucleus. This implies the probability of formation of heavier masses in the reaction process with heavier isotope of the projectile as well as target. In Ref. [14], within the formalism of a Thomas-Fermi model, calculations are presented for nuclei beyond the nuclear drip-line at zero temperature. This is possible because of the presence of an external neutron gas which may be envisaged in the astrophysical scenario and is the situation of the present discussion for accreting cosmological objects.

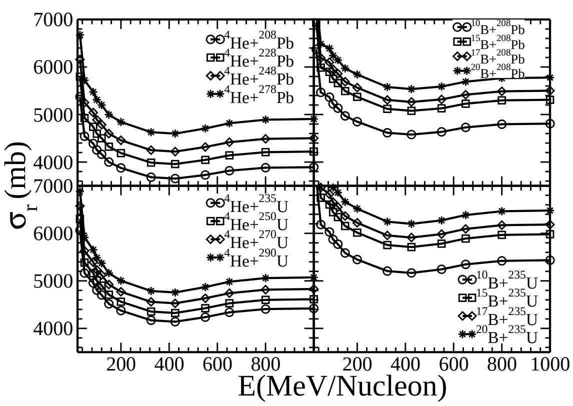

Figure 1. *The nuclear reaction cross-sections taking He and B isotopes as projectile with different isotopes of Pb and U.*

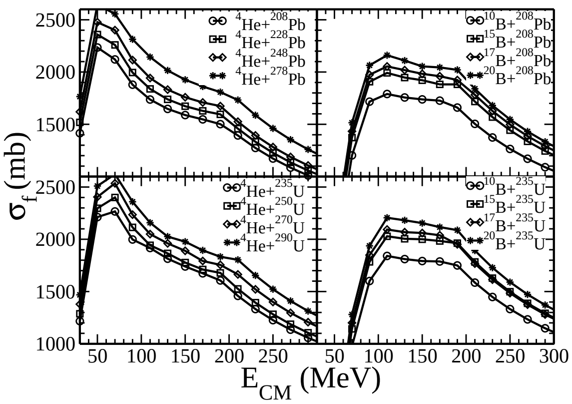

Figure 2. *The nuclear fusion cross-sections taking He and B isotopes as projectile with different isotopes of Pb and U.*

In Fig. 2 the fusion cross-section σ_f for various neutron-rich light nuclei with heavier drip-line isotopes, like ^{4}He+^{208,228,248,278}Pb, ^{10,15,17,20}B+^{208}Pb, ^{4}He+^{235,250,270,290}U and ^{10,15,17,20}B+^{235}U are shown. Similar to the reaction cross-section, the increase in σ_f is quite clear with the increase of target, projectile or both the masses. This implies the probability of creation of heavier masses with the increase of mass number of the projectile as well as target and making the way for the evolution of neutron-rich heavy nuclei much beyond the drip-line [14] due to the presence of the external neutron gas or highly neutron-rich light as well as heavy nuclei generates in the astrophysical objects,in the relativistic jets of GRBs or supernovae jets near the nascent neutron star. Analysis of figures 1 and 2 shows that, the magnitude of σ_r and σ_f are optimum at $\sim$ 30 to 200 MeV of the incident projectile energy. Beyond this range, the value of σ_r and σ_f decreases drastically. Both the cross-sections indicate the suitability of the incident projectile energy for a favourable condition of the formation of the fused elements in the astrophysical system. Thus, the chance of the formation of heavier element is maximum, if a suitable energy range is created, which may be a source in the relativistic jets of GRBs or supernovae jets near the nascent neutron star [15,16]. The high energy environment in such cosmological objects is because of the supernova shock [17] and it is quite common in the nascent neutron star or relativistic jest of GRBs [15,16]. In these objects a highly neutron-rich and high temperature scenario is made possible and which may be a probable platform for such reactions.

In this context, it is worth citing the following

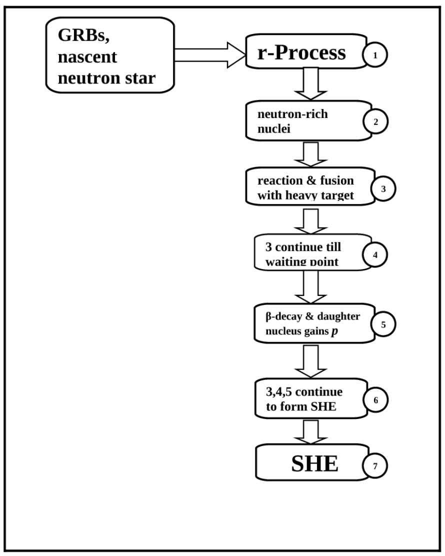

Figure 3. *The schematic diagram for the formation of superheavy element (SHE) in the astrophysical object such as relativistic jets of GRBs or supernovae jets near the nascent neutron star. The production of SHE is possible through reaction and fusion processes at a favourable energy condition in the cosmos.*

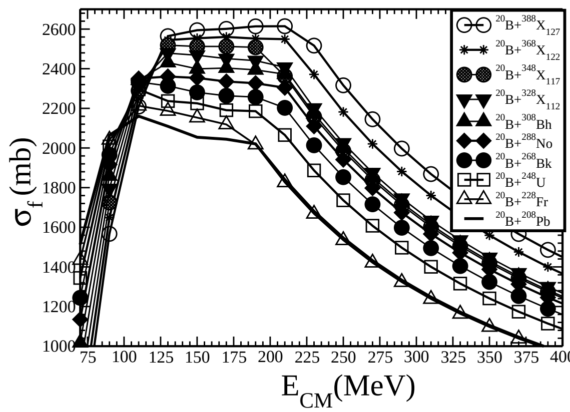

Figure 4. *A representative path for the formation of $^{408}X_{132}$ superheavy element through ^{20}B capture process. The fusion cross-sections σ_f for various daughter nuclei with ^{20}B is shown.*

example: A neutron star is borned when a star of mass $\sim 20\ M_\odot$ undergoes its core collapses after hyper-energetic explosions of Gamma ray bursts. A star with initially $\sim 20\ M_\odot$ would develop carbon-oxygen core of $\sim 3.3\ M_\odot$. It left behind a neutron star of $\sim 1.4\ M_\odot$, $\sim 1.3\ M_\odot$ of oxygen and $\sim 0.6\ M_\odot$ of heavier elements, Si and Fe group, which could be ejected in the supernova. Such a collapse gives rise to an explosion of kinetic energy K.E. $\sim 10^{51}$ ergs ($\sim 6.25\times10^{56} MeV$) [15,16].

Young neutron stars have a fluid surface, a solid, crystalline crust and a fluid interior. The fluid regions of the star adjust themselves to its rotation which remaining always axi-symmetric. The radiated power comes directly from the rotational energy of the neutron star. The entropy in mass elements exhibiting the neutron star at later times will be larger than the earlier. This is because, most of the heating occurs near the surface of the neutron star. Slowly with time the radius of the neutron star shrinks from $100 Km$ to $10 Km$ [18]. The decrease in the initial radius start from which the mass elements begin increasing the heat rate [15,16].

It is worth mentioning of the burning process of H, He, Li, ... in the accreting astrophysical system. To maintain *hydrostatic equalibrium* [19], this continues upto formation of Iron. When this stage is reached, depending on its mass, the astrophysical object undergoes various phenomena like supernovae explosion, X-rays burst, GRBs, formation of neutron star, black hole, red giant or white dwarf etc. In some cases, it becomes highly neutron-rich environment (novae, supernovae or X-rays burst or neutron star) and is favourable for rn-process, which continue upto certain A or Z

number. Slowly, this rn-capture process becomes less favourable and fusion of light nuclei (like He, Li, Be,...) become more important. In the mean time, the neutron-rich light element fused with these heavy nuclei and more heavier isotopes with a little increase of proton number is generated in the process; for example, ^{4}He+^{208}Pb gives ^{212}Po. Again ^{212}Po reacts with ^{4}He to form ^{216}Rn. A schematic diagram for the process of SHE formation is shown in Figure 3. From the figure, it can be understood how this phenomenon goes on to create much heavier isotopes. Similarly other processes also continue to go on as shown in figures 1, 2 and 3, such as ^{20}B+^{235}U$\rightarrow$ ^{255}Bk, ^{20}B+^{255}Bk $\rightarrow$^{275}No, ... and so on.

A representative example is depicted in Figure 4. As mentioned earlier, after the supernovae explosion, in the rn-process, heavy normal/exotic nuclei including the ultra-neutron-rich light isotopes are formed. Exotic nuclei like ^{6}He, ^{11}Li, ^{14}Be, ^{20}B, normal actinides (e.g. ^{208}Pb, ^{235}U etc.) and neutron-rich drip-line isotopes, similar to ^{278}Pb etc. are generated. Thereafter, fusion process of the light isotopes with heavier nuclei becomes important. The increase of fusion cross-sections as shown in Fig. 4 confirmed the possibility of the formation of ultra-heavy isotopes as well as superheavy elements both with lower and higher atomic masses. The demonstration of a path for the formation of $^{408}X_{132}$ (A=408, Z=132, N=276) through complete fusion process is given below (whose cross-sections are shown in Fig. 4): ^{20}B+^{208}Pb $\rightarrow$ ^{228}Fr, ^{20}B+^{228}Fr $\rightarrow$ ^{248}U, ^{20}B+^{248}U $\rightarrow$ ^{268}Bk, ^{20}B+^{268}Bk $\rightarrow$ ^{288}No, ^{20}B+^{288}No $\rightarrow$ ^{308}Bh, ^{20}B+^{308}Bh $\rightarrow$ $^{328}X_{112}$, ^{20}B+$^{328}X_{112}$ $\rightarrow$ $^{348}X_{117}$, ^{20}B+$^{348}X_{117}$ $\rightarrow$ $^{368}X_{122}$, ^{20}B+$^{368}X_{122}$ $\rightarrow$ $^{388}X_{127}$, ^{20}B+$^{388}X_{127}$ $\rightarrow$ $^{408}X_{132}$ and so on.

Thus, each time the proton number Z increases by 5 units the mass number A goes up by 20 units in the case of ^{20}B capture. Slowly, it creates a highly neutron-rich heavy isotope, which is enabled to capture any more neutron n or neutron-rich nucleus. This is termed as *waiting point.* Here, the neutron-rich heavy element emits a $\beta^{-}-$ particle, and the daughter nucleus gains a positive charge by converting a neutron (n) to a proton (p). Due to this enhancement in Z, the product (daughter nucleus) captures few more n or neutron-rich light nuclei by fusion process till it reaches the new waiting point. At this point, the nucleus gains another proton p, by emitting $\beta^{-}-$particle. This process continues and SHE or super-SHE are formed in the cosmoligical object. In this context, it is worth mentioning that, the dominant mode of decays are β^{-} and spontaneous fission for large N and large Z nuclei, respectively. In the $\beta^{-}-$ decay, the daughter nucleus gains a proton, whereas for large N, the spontaneous fission reduces considerably due to excess number of neutrons [5] and the neutron-rich isotope becomes fission stable as the height of the fission barrier decreases and the width increases, thereby making the nucleus more stable against fission [5]. It is interesting to mention here that, recently it has been reported by A. Marinov et al. [20], that the evidence of a superheavy isotope with $Z = 122$ or 124 and a mass number A=292; has been found in natural Th using inductively coupled plasma-sector field mass spectrometry. The estimated half-life of this isotope is $t_{1/2} \geq 10^{8}$ years, comparable with the theoretical predictions [3].

In summary, we estimated the reaction and fusion cross-section of various combination of light and heavy isotopes. We extended the calculations to exotic systems taking into consideration the possibility of availing the rn-process and the exotic nuclei capture processes in astrophysical objects. The enhanced cross-sections with increase of mass number for both the projectile and target made it possible for the formation of the heavier neutron-rich nuclei way beyond the normal drip-lines predicted by the mass models. By the neutron or heavy ion (light neutron-rich nuclei) capture process the daughter nucleus becomes a superheavy element which may be available somewhere in the Universe in super-natural condition and can be possible to be synthesised in laboratories. Here the stability of the neutron-rich SHE or super-SHE against spontaneous fission arises due to widening of the fission barrier because of the excess number of neutrons.

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REFERENCES

1. Yu. Ts. Oganessian et al., Phys. Rev. **C74** (2006) 044602.
2. P. Möller and J.R. Nix, Nucl. Phys. **A549** (1992) 84 .
3. S.G. Nilsson, J.R. Nix, A. Sobiczewski, Z. Szymafiski, S. Wycech, C. Gustafson and P. Mö11er, Nucl. Phys. **A115**, (1968) 545; S.G. Nilsson, C.F. Tsang, A. Sobiczewski, Z. Szymafiski, S. Wycech, C. Gustafson, I.-L. Lamm, P. Mö11er and B. Nilsson, Nucl. Phys. **A131** (1969) 1; M. Brack, J. Damgaaid, A.S. Jensen, H.C. Pauli, V.M. Strutinsky and C.Y. Wong, Rev. Mod. Phys. **44** (1972) 185; E.O. Fiset and J.R. Nix, Nucl. Phys. **A193** (1972) 647; J.R. Nix, Ann. Rev. Nucl. Sci. **22** (1972) 65.
4. A. Ozawa, T. Suzuki and I. Tanihata, Nucl. Phys. **A693** (2001) 32.
5. L.Satpathy, S.K. Patra and R.K. Choudhury, PRAMANA - J. Phys. **70** (2008) 87.
6. R.J. Furnstahl, B.D. Serot and H.B. Tang, Nucl. Phys. **598** (1996) 539; R.J. Furnstahl, B.D. Serot and H.B. Tang, Nucl. Phys. **615** (1997) 441; B. D. Serot and J. D. Walecka, Int. J. Mod. Phys. **E 6** (1997) 515; R.J. Furnstahl and B.D. Serot, Nucl. Phys. **671**, (2000) 447.
7. R. J. Glauber, *Lectures on Theoretical Physics, edited by* W. E. Brittin and L. C. Dunham Interscience,vol.1, New York, 1959, P.315.
8. P. Shukla, Phys. Rev. **C67** (2003) 054607.
9. M.Y.H. Farag, Eur. Phys. J. **C12** (2001) 1112; S. K. Charagi and S. K. Gupta, Phys. Rev. **C41** 1610 (1990) 1610; S. K. Charagi, Phys. Rev. **C48** 452 (1993) 452.
10. A. Shukla, B. K. Sharma, R. Chandra, P. Arumugam and S. K. Patra, Phys. Rev. **C76** (2007) 034601 ; B.K. Sharma, S.K. Patra, Raj K. Gupta, A. Shukla, P. Arumugam, P.D. Stevenson and Walter Greiner, J. Phys. **G32** (2006) 2089 .
11. M. Del Estal, M. Centelles, X. Viñas and S. K. Patra, Phys. Rev. **C63** (2001) 044321 ; S. K. Patra, M. Del Estal, M. Centelles and X. Viñas, Phys. Rev **C63** (2001) 024311 .
12. B.A. Ibrahim, Y. Ogawa, Y. Suzuki and I. Tanihata, Comp. Phys. Comns. **151** (2003) 369 .
13. K. Hagino, N. Rowley and A.T. Kruppa, Comp. Phys. Comm. **123** (1999) 143.
14. J. N. De, X. Viñas, S. K. Patra, and M. Centelles, Phys. Rev. **C64** (2001) 057306.
15. P. A. Mazzali, J. Deng, K. Nomoto, D. N. Sauer, E. Pian, N. Tominaga, M. Tanaka, K. Maeda and A. V. Filippenko, Nature **442** (2006) 1018.
16. T. A. Thompson, P. Chang and E. Quataert, Astrophys. Jour. **611** (2004) 380.
17. P. O. Lagage and C.J. Cesarsky, Astron. Astrophys. **125** (1983) 249.
18. J.R. Wilson and R.W. Mayle, Phys. Rep. **227** (1993) 97; B.S. Meyer, Annu. Rev. Astron. Astrophys. **32** (1994) 153.
19. J.M. Pearson *Nuclear Physics: Energy and Matter,* Ch. II, Adam Hilger Ltd, 1986, P. 87.
20. A. Marinov, I. Rodushkin, D. Kolb, A. Pape, Y. Kashiv, R. Brandt, R.V. Gentry and H.W. Miller, arXiv:nucl-ex/0804.3869.